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## LATE NEOGENE ELASMOBRANCH FAUNA FROM THE COQUIMBO FORMATION, CHILE

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**ABSTRACT** – Neogene marine sediments from Chilean geological formations contain a diverse marine fossil fauna. In Chile, the “Norte Chico” (27°S to 32°S) is composed of two important sedimentary marine deposits, the Bahía Inglesa and Coquimbo formations. Diverse vertebrate taxa including fish, birds, mammals and abundant chondrichthyans have been described from Bahía Inglesa Formation. However, the vertebrate fauna from Coquimbo Formation has been poorly documented. Based upon field trips and the analysis of collections from the Coquimbo Formation, the elasmobranch fossil fauna is composed of at least nine taxa, two of which are extinct (*Carcharocles megalodon* and *Carcharodon plicatilis*). The rest of the taxa are related with living elasmobranch species that are inhabitants of the Eastern Pacific Ocean and Tropical America coast.

**Key words:** Neogene, shark, elasmobranch, chondrichthyans, Coquimbo Formation, Pacific.

**RESUMO** – Sedimentos marinhos de formações geológicas chilenas do Neógeno contêm uma diversa fauna fóssil marinha. No Chile, o “Norte Chico” (27°S to 32°S) é composto de dois importantes depósitos sedimentológicos marinhos, as formações Bahía Inglesa e Coquimbo. Uma diversidade de táxons de vertebrados, que inclui peixes, aves, mamíferos além de abundantes chondrichthies, têm sido descritos para a Formação Bahía Inglesa. Entretanto, a fauna de vertebrados da Formação Coquimbo está pobremente documentada. Com base em trabalhos de campo, bem como na análise de coleções da Formação Coquimbo, observa-se uma fauna de elasmobrânquios composta de pelo menos nove táxons, dois dos quais estão extintos (*Carcharocles megalodon* e *Carcharodon plicatilis*). Os demais táxons estão relacionados com as espécies de elasmobrânquios recentes que habitam as costas leste do Oceano Pacífico Leste e da América Tropical.

**Key words:** Neógeno, tubarão, elasmobrânquio, condricthios, Formação Coquimbo, Pacífico.

## INTRODUCTION

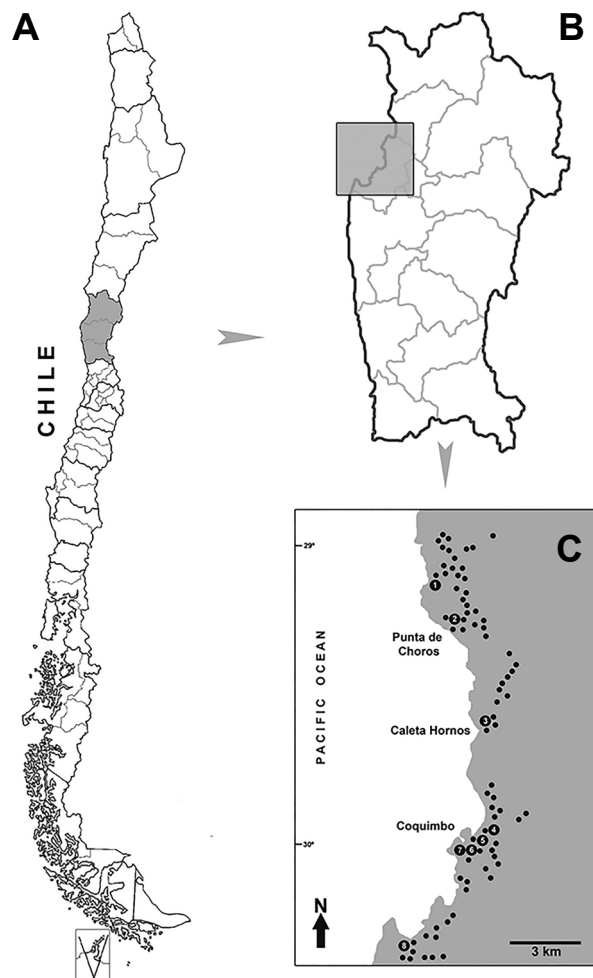
Evidence of fossil elasmobranchs has been collected from Neogene marine sediments distributed all over the world (Cappetta, 2012). As an example, fossil elasmobranch teeth have been collected and studied from four main Chilean geological formations: Bahía Inglesa (27°S), Coquimbo (between 29°S to 30°S), Horcón (32°S) and Navidad (33°S) (Philippi, 1887; Gigoux, 1944; Long, 1993; Arratia & Cione, 1996; Suárez & Encinas, 2002; Suárez & Marquardt, 2003; Suárez *et al.*, 2004; Carrillo-Briceño *et al.*, 2013). These marine fossil deposits have been commonly found in the northern coast of Chile, and characterized by a high proportion of fossil elasmobranch teeth (*e.g.* Suárez & Marquardt, 2003). This particular geographic area is called the “Norte Chico”, and is composed of two geological formations: Bahía Inglesa and Coquimbo. The Bahía Inglesa Formation was deposited under marine conditions, and has been well studied geologically (Rojo, 1985; Marquardt, 1999). Different taxa of fish, birds and mammals have been referred from Bahía Inglesa (Long, 1993; Arratia & Cione, 1996; Walsh & Hume, 2001; Walsh & Naish, 2002; Suárez *et al.*, 2004; Acosta *et al.*, 2006; Chávez, 2008), and at least 23 taxa of chondrichthyan species have been described as well (Long, 1993; Arratia & Cione, 1996; Suárez & Marquardt, 2003; Suárez *et al.*, 2004). Unfortunately, craftsmen and private collectors recurrently visit the marine sediments in Bahía Inglesa to remove and sometimes sell the fossils.

In comparison with the knowledge of the marine vertebrate fauna from Bahía Inglesa, little is known about the vertebrate marine fossil fauna from the Coquimbo Formation (Philippi, 1887; Long, 1993). The area of Coquimbo has experienced urban and industrial expansion during the last two decades. Consequently, most of the marine fossil deposits have been disturbed, and many of them are now destroyed or buried. In this context, the aim of this study was to characterize the elasmobranch fossil marine deposits from the Coquimbo Formation by describing fossil teeth found under the surface ground layer before the complete destruction of the locality.

## MATERIAL AND METHODS

The material examined consists of isolated elasmobranch fossil teeth that have been collected in different locations from the Coquimbo Formation: Caleta Chañaral, Punta de Choros, Caleta Hornos, La Cantera Baja, La Herradura, Quebrada Las Rosas and El Rincon (Figure 1). The localities La Cantera Baja, La Herradura and Quebrada Las Rosas were already impacted by urbanization. The sampling design consisted of alternating between surface surveys and bulk samples with excavations of up to 1 m depth. Fossil shark teeth are commonly found in the surface layer in the Coquimbo Formation.

This material is deposited at the Museo Arqueológico de La Serena (MALS), La Serena, Chile. The classifications follow Compagno (1973, 1977) and the terminology is based on Cappetta (2012). Measurements taken include height and width, and these refer to the entire tooth including



**Figure 1.** A, map showing the regional representation of Chile. The Coquimbo region is shown in gray color. B, zoom in of the Coquimbo region; the gray square represents the study area. The light gray lines are indicating the fourteen areas distributed in this region. C, map showing the locations where the elasmobranch fossils were found. The black dot represents the locations: 1, Caleta Chañaral; 2, Punta de Choros; 3, Caleta Hornos; 4, La Cantera Baja; 5, Quebrada El Culebrón; 6, Quebrada Las Rosas; 7, La Herradura; 8, El Rincón.

the root. Taxonomic identification included an extensive bibliographical review and comparative studies of fossil and extant specimens from: Museo Nacional de Historia Natural de Santiago (SGO-PV) in Chile, Museo Paleontológico de Caldera (MPC), Atacama, both in Chile and Natural History Museum of Basel (NMB), Switzerland; Paleontological collections of the Alcaldía Bolivariana de Urumaco (AMUCURS), Venezuela; Palaeontological Institute and Museum at the University of Zurich (PIMUZ), Switzerland.

## GEOLOGICAL SETTINGS

Flat terraces of sedimentation characterize the Coquimbo Formation. These are composed of neritic or sublittoral marine sediments that are fine to medium-grained (Le Roux *et al.*, 2004). Small-cemented yellowish sand is also present, along

with blocks displaced from the bedrock. Shell middens are commonly found in banks between 0.40 and 2 m thickness, on the surface or in sectors with a whitish calcareous crust on the ground (Paskoff, 1970; Le Roux *et al.*, 2004; Acosta *et al.*, 2006). Although the shell middens are mostly from the Plio-Pleistocene, the Miocene transgression seems to be mostly responsible for most of the marine sediment (Le Roux *et al.*, 2006). In this study, shark fossil teeth were obtained from areas near beaches such as marine terraces close to the sea or streams. The terraces have a relative distance of up to 2 km from the coastline and a peak height of 81 meters (Le Roux *et al.*, 2006). Paskoff (1970) suggests a height of 80 m for the outcrop of the Miocene transgression, but some shark fossil teeth can be found in secondary deposits due to relief changes associated with neotectonics. These changes were very important in structuring the relief of the coast during the Plio-Quaternary (Radtke, 1989).

The age of the Coquimbo Formation could be extended backward in time to about 15 Ma (middle Miocene). Fossil invertebrates suggest that all locations sampled in this study originated from Pliocene sedimentary depositions of marine fauna (Herm, 1969). A study based on the potassium-argon radioisotope suggests that the Coquimbo Formation is upper Miocene in age, of around 6 million years ago (Chávez *et al.*, 2007). In addition, thirteen stratigraphic units were identified in the Coquimbo Formation using faunal remains and lithological features (Le Roux *et al.*, 2004). A maximum age of 2 Ma was estimated using strontium from microfossil remains found in the top of the stratigraphic unit (middle Miocene to late Pliocene; Le Roux *et al.*, 2004). The second stratigraphic unit is from Langhian sediment and it has associated with the base of the Coquimbo Formation (Le Roux *et al.*, 2004; Acosta *et al.*, 2006). As a result of these estimations, we propose an age close to the middle Miocene-late Pliocene for the Coquimbo Formation.

The stratigraphic sequence from Quebrada Las Rosas is composed of marine invertebrates and vertebrates (see Figure 2). The basal stratum comprised lime and clay with fossil mollusks and shark teeth. The median stratum is sandy and made of conglomerates of mollusks. The upper stratum is formed of fine sand with a layer of invertebrates. However, this is a general description and we are not able to provide further details because of the lack of stratigraphic studies. A similar formation is observed in Bahía Inglesa Formation (BIF) with common records of shark teeth composed of a large spectrum of taxa (Suárez & Marquardt, 2003; Rivadeneira & Varas, 2012).

## SYSTEMATIC PALEONTOLOGY

Order LAMNIFORMES Berg 1937  
Family †OTODONTIDAE Glikman, 1964

†*Carcharocles* Jordan & Hannibal, 1923

†*Carcharocles megalodon* (Agassiz, 1843)  
(Figures 3A-C)

**Material.** Four lower lateral teeth (MNHN SGO. 58, Coquimbo; MALS P-228, Punta de Choros; MALS P-6564, Quebrada Chañaral de Aceitunas; MALS P-227, Quebrada El Culebrón).

**Description.** Teeth have a triangular, broad and slightly symmetrical crown. The lingual face of the crown is flat and the labial is convex with a typical large neck, clearly observed in the specimen MNHN SGO. 58. The crown in the rest of the specimens is poorly preserved. Both cutting edges have a fine serration. The root has well developed lobes and a weak lingual protuberance. The teeth range in height between 32 and 98 mm and width between 35 to 93 mm. The largest tooth is the specimen MALS P-228, with 98 mm in height and 93 mm in width.

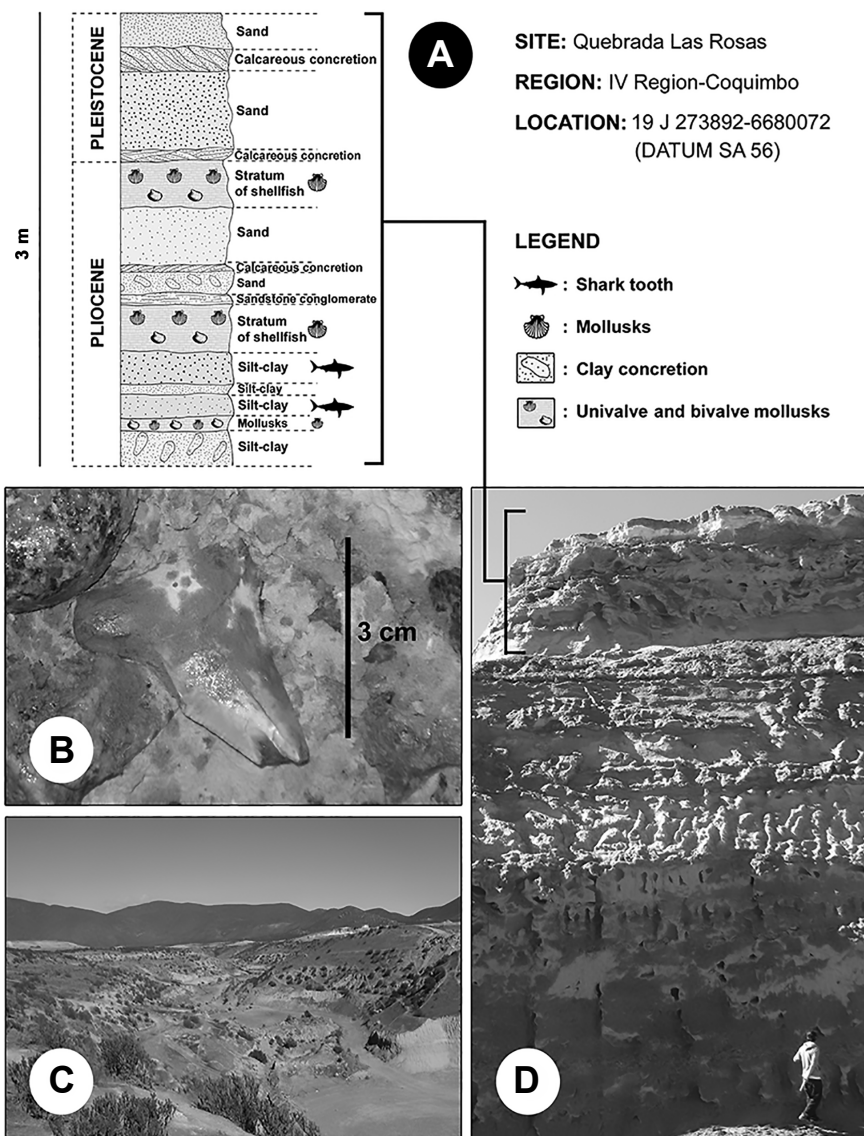
**Remarks.** *Carcharocles* was a cosmopolitan species and its fossil record has been reported from almost all Neogene sedimentary deposits that contain shark teeth (García *et al.*, 2009). In the Neogene deposits, *Carcharocles* is mainly represented by *C. chubutensis* Ameghino, 1901 and *C. megalodon* Agassiz, 1843 (e.g. Pimiento *et al.*, 2010, 2013a,b; Cappetta, 2012; Pimiento & Clements, 2014). *C. megalodon* has a stratigraphic range from the middle Miocene to the late Pliocene (Pimiento & Clements, 2014), whereas *C. chubutensis* has been restricted to the early/middle Miocene (Pimiento & Clements, 2014). However, taxonomical distinctions and generic identification between the taxa have been debated over the years. The classification of *Carcharocles* lineage is still discussed (Pimiento *et al.*, 2010, 2013b; Reinecke *et al.*, 2011; Cappetta, 2012; Bor *et al.*, 2012). From the Neogene of Chile, *C. megalodon* has been reported from the Bahía Inglesa and Lo Abarca formations (Long, 1993; Walsh, 2001; Encinas, 2002; Suárez & Encinas, 2002; Suárez *et al.*, 2004). Philippi (1887) reported an isolated tooth of *C. megalodon* with unclear origin from Coquimbo region. The specimens of *C. megalodon* from the Coquimbo Formation extend the southern distribution on the Eastern Pacific during the late Neogene. An overview of the *C. megalodon* is show by Carrillo-Briceño *et al.* (2013) from America fossil records.

Family LAMNIDAE Müller & Henle, 1838

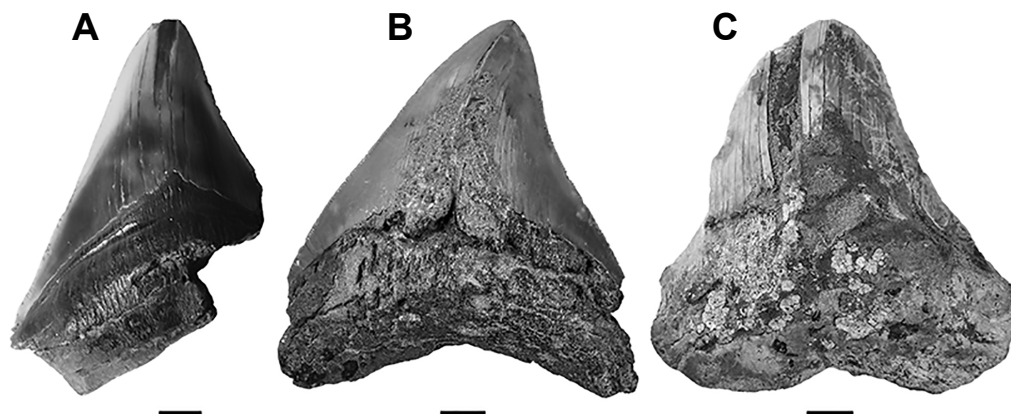
*Carcharodon* Smith in Müller & Henle, 1838

*Carcharodon carcharias* Linnaeus, 1758  
(Figure 4A)

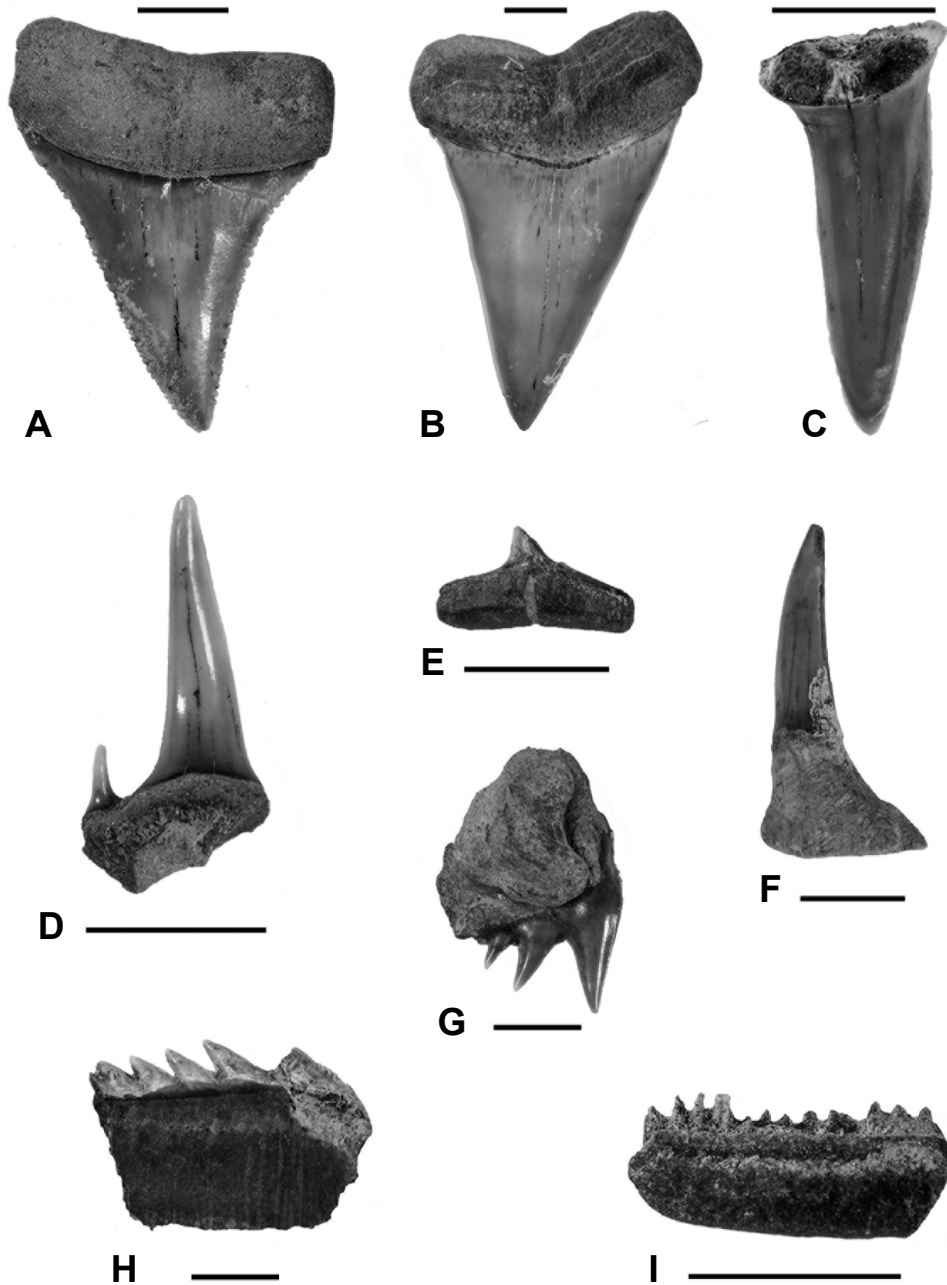
**Material.** Fifty upper lateral teeth (MALS P-59, MALS P-60, MALS P-64, Quebrada El Culebrón; MALS P-79, MALS P-80, MALS P-83, MALS P-84, MALS P-86, MALS P-87, MALS P-88, MALS P-90, MALS P-92, MALS P-105, La Cantera Baja; MALS P-119, MALS P-126, MALS P-127, Quebrada Las Rosas; MALS P-131, MALS P-133, Caleta Chañaral; MALS P-142, MALS P-143, MALS P-144, MALS P-150, MALS P-151, MALS P-152, MALS P-159, MALS P-160, MALS P-161, MALS P-163, MALS P-164, MALS P-165, MALS P-166, MALS P-169, MALS P-170,



**Figure 2.** **A**, geological stratigraphic units showing the association of elasmobranchs found in the Coquimbo Formation. **B**, *Carcharodon carcharias* fossil tooth found on silt-clay mixed with stones and sedimentary soil. **C**, landscape of sedimentary terraces of the Coquimbo Formation located in Quebrada Las Rosas. **D**, general view of stratigraphic units from Quebrada Las Rosas.



**Figure 3.** *Carcharocles megalodon* fossil teeth. **A**, MNHN SGO.58, lower lateral tooth in labial view; **B**, MALS P-6564, lower lateral tooth in labial view; **C**, MALS P-228, lower lateral in labial view. Scale bars = 10 mm.



**Figure 4.** Elasmobranch fossil teeth. **A**, *Carcharodon carcharias*, MALS P-87, upper lateral tooth in labial view. **B**, *Carcharodon plicatilis*, MALS P-63, upper lateral tooth in labial view. **C**, *Isurus* cf. *I. oxyrinchus*, MALS P-199, upper anterior tooth in labial view. **D**, *Odontaspis ferox*, MALS P-104, lateral tooth in labial view. **E**, *Carcharhinus* sp. MALS P-111, lower lateral tooth in labial view. **F**, *Pristiophorus* sp., MALS P-75, rostral tooth. **G**, *Hexanchus* cf. *H. griseus*, MALS P-108, upper anterior tooth in lingual view. **H**, *Hexanchus* cf. *H. griseus*, MALS P-225, lower lateral tooth in lingual view. **I**, *Myliobatis* sp., MALS P-231, symphysial tooth of in lingual view. Scale bars = 10 mm.

MALS P-176, MALS P-177, MALS P-178, MALS P-179, MALS P-184, MALS P-189, MALS P-190, MALS P-193, MALS P-197, MALS P-198, La Herradura; MALS P-203, MALS P-206, MALS P-208; MALS P-212, MALS P-216, MALS P-217, MALS P-219, Quebrada El Culebrón), one upper posterior tooth (MALS P-114, La Cantera Baja), three upper teeth (MALS P-147, MALS P-181, MALS P-185, La Herradura), ten upper anterior teeth (MALS P-85, MALS P-93, La Cantera Baja; MALS P-116, Quebrada Las Rosas; MALS P-146, MALS P-155, MALS P-186, MALS P-191,

MALS P-194, La Herradura; MALS P-210, MALS P-220, Quebrada El Culebrón), three lower posterior teeth (MALS P-78, MALS P-113, La Cantera Baja; MALS P-148, La Herradura), fourteen lower lateral teeth (MALS P-81, MALS P-82, MALS P-91, La Cantera Baja; MALS P-129, MALS P-130, Quebrada Las Rosas; MALS P-145, MALS P-149, MALS P-171, MALS P-196, La Herradura; MALS P-207, MALS P-209, MALS P-211, MALS P-2014, MALS P-215, Quebrada El Culebrón), six lateral teeth (MALS P-117, MALS P-128, Quebrada Las Rosas; MALS P-153, MALS

P-162, MALS P-173, La Herradura; MALS P-223, Quebrada El Culebrón), twenty lower anterior teeth (MALS P-89, La Cantera Baja; MALS P-141, MALS P-154, MALS P-156, MALS P-168, MALS P-172, MALS P-174, MALS P-180, MALS P-182, MALS P-183, MALS P-192, MALS P-195, La Herradura; MALS P-204, MALS P-205, MALS P-213, MALS P-218, MALS P-221, MALS P-222, MALS P-224, Quebrada El Culebrón) and one unknown position tooth (MALS P-157, La Herradura).

**Description.** Upper and lower teeth have a broad, triangular and slightly elongated labio-lingually compressed crown. The labial face is flattened whereas the lingual is convex; both cutting edges are coarse serrated. The basal portion of the crown is in contact with roots and lacks enamel, forming a thin dental band, observable on the labial and lingual surface. Root with two well-defined lobes that are straight or it may present a U-shaped arch in some specimens. The teeth range in height between 10 and 73 mm and width between 10 to 47 mm.

**Remarks.** The fossil record of *Carcharodon carcharias* is known from the lower Pliocene to recent, and it has been referred to Africa, Asia, Australia, Europa and North and South America (Kemp, 1991; Cappetta, 2012; Ehret *et al.*, 2012; Cione *et al.*, 2012; Carrillo-Briceño *et al.*, 2013). The fossil record of *C. carcharias* from the late Neogene of Chile is abundant, mainly from the Pliocene strata of the Bahía Inglesa Formation (Long, 1993; Walsh, 2001; Quilodran & Marquardt, 2001; Walsh & Naish, 2002; Suárez & Marquardt, 2003). However, some specimens have been dubiously referred to the late Miocene strata of this unit (e.g. Bianucci *et al.*, 2006). Other fossil record of *C. carcharias* from Chile include the following localities: Bahía Salado, Bahía Tongoy, Cuenca del Tiburon, Horcón, La Cueva, and La Portada (Suárez & Brito, 2000; Emslie & Correa, 2003; Suárez & Marquardt, 2003; Le Roux *et al.*, 2006; Carrillo-Briceño *et al.*, 2013). Cione *et al.* (2012) and Carrillo-Briceño *et al.* (2013) provided a summary of the fossil record of *C. carcharias* in South America.

†*Carcharodon plicatilis* Agassiz, 1843  
(Figure 4B)

**Material.** Upper lateral tooth (MALS P-63, El Rincón).

**Description.** The tooth has a wide, triangular and labio-lingually compressed crown. The cutting edges are sharp without any serration. The root is compressed with two lobes, and the base shows a concavity forming an inverted V. The tooth measures 50 mm in height and 36 mm in width.

**Remarks.** Several morphological aspects of the taxonomic classification of this species have been debated over the years, without consensus (e.g. Purdy *et al.*, 2001; Cappetta, 2012; Cione *et al.*, 2012; Ehret *et al.*, 2012). Previous taxonomic assignments have included some species of “wide-toothed shape” such as *Isurus planus* Agassiz, 1856, *Isurus hastalis* Agassiz, 1838 and *Isurus xiphodon* Agassiz, 1838 to *Cosmopolitodus* (Cappetta, 2006, Cione *et al.*, 2012). Ehret *et al.* (2012) included *Cosmopolitodus* to

*Carcharodon*, proposing a transition between *Carcharodon hastalis* and *Carcharodon carcharias*. Ward & Bonavia (2001) suggested the recognition of only one species, and proposed that *C. xiphodon* is a *nomen dubium* because of the uncertainty implied in differentiating *Cosmopolitodus hastalis* from *Cosmopolitodus xiphodon*. According to Cione (1988), Purdy *et al.* (2001) and Cione *et al.* (2012), there is a species that appears to be the putative sister group of *Carcharodon carcharias* and different from *Cosmopolitodus hastalis*. Cione *et al.* (2012) proposed this species as “*Isurus*” *plicatilis* Agassiz, 1843, which is recognized as an available and valid taxon. According to Cione *et al.* (2012), only *plicatilis* or *xiphodon* [adapting latter from Purdy *et al.* (2001)] should be referred to the genus *Carcharodon*. Hereby, we adopt the taxonomic proposal suggested by Cione (1988) and Cione *et al.* (2012). In the Neogene of Chile, *Carcharodon plicatilis* has been reported from the Bahía Inglesa, Navidad and Coquimbo formations (Long, 1993; Quilodran & Marquardt, 2001; Walsh, 2001; Suárez & Encinas, 2002; Walsh & Naish, 2002; Suárez & Marquardt, 2003; Le Roux *et al.*, 2006).

*Isurus* Rafinesque, 1810

*Isurus* cf. *oxyrinchus* Rafinesque, 1810  
(Figure 4C)

**Material.** Upper lateral tooth (MALS P-58, Caleta Chañaral), upper anterior tooth (MALS P-199, Caleta de Hornos), lower anterior tooth (MALS P-134, Caleta Chañaral) and anterior tooth, unknown jaw position (MALS P-188, La Herradura).

**Description.** Three teeth are incomplete with damaged roots (MALS P-134, MALS P-188, MALS P-199). In anterior teeth the crown is elongated, asymmetrical, distally inclined and with smooth sharp cutting edges; its apex is sharp-pointed. The lateral has a triangular crown slightly inclined distally. There is an evident lingual protuberance with a transverse groove. The only complete tooth (MALS P-58) measures 25 mm in height and 12 mm in width.

**Remarks.** *Isurus oxyrinchus* has a stratigraphic record from the late Oligocene to present with a cosmopolitan paleodistribution (Reinecke, 2011). Despite the fact that the specimens from the Coquimbo Formation are mostly incomplete, they exhibit a close resemblance to teeth of the extant *I. oxyrinchus*, allowing the association of the fossils with this taxon. In Chile, the fossil record of *I. oxyrinchus* appears regularly along the central coast of the Bahía Inglesa Formation (Suárez *et al.*, 2002; Walsh, 2001; Long, 1993; Suárez & Marquardt, 2003; Suárez *et al.*, 2004). In contrast to Bahía Inglesa, *I. oxyrinchus* fossil teeth are less frequent southward. However, this species has been found in marine sediments from Lo Abarca, Navidad and Horcón formations (Encinas, 2002; Suárez & Encinas, 2002; Suárez & Marquardt, 2003; Suárez *et al.*, 2006; Carrillo-Briceño *et al.*, 2013).

Family ODONTASPIDIDAE Müller & Henle, 1839

*Odontaspis* Agassiz, 1838

*Odontaspis ferox* Risso, 1810  
(Figure 4D)

**Material.** Lateral tooth (MALS P-104, La Cantera Baja).

**Description.** The crown is elongated and slender with sharp and smooth cutting edges. Fossil and extant specimens of *Odontaspis ferox* show between three and one lateral cusplets (e.g. Purdy *et al.*, 2001). However, the specimen MALS P-104 preserves only one cusplet as a consequence of the damaged root. The root shows an evident lingual protuberance. The incomplete tooth is 22 mm in height.

**Remarks.** *Odontaspis ferox* has a fossil record from the Miocene to recent (Purdy *et al.*, 2001; Aguilera & Rodríguez de Aguilera, 2001; Marsili, 2007). During the Paleocene-Eocene, this species is considered as the dominant group of Patagonia of Chile and Argentina, as well as of other ancient temperate seas around the world (e.g. Eocene of Seymour Island, Antarctica) (Arratia & Cione, 1996). This species has been reported to the Bahía Inglesa (Suárez *et al.*, 2002) and Navidad formations (Suárez & Encinas, 2002; Suárez & Marquardt, 2003).

Order CARCHARHINIFORMES Compagno, 1973  
Family CARCHARHINIDAE Jordan & Evermann, 1896

*Carcharhinus* Blainville, 1816

*Carcharhinus* sp.  
(Figure 4E)

**Material.** Three lower lateral teeth (MALS P-110, MALS P-112, La Cantera Baja; MALS P-111, La Cantera).

**Description.** The fossil teeth are fragmented, preserving only the crown or the root. The crown is triangular and decreases in size toward the apex of the tooth. The crown is distally inclined towards the right with fine serration along the cutting edges (MALS P-110). The root has broad lobes with slightly basal concavity and a shallow nutritive groove (MALS P-111). Diagnostic characters of the species are difficult to identify because of the fragmented condition and poor preservation of the specimens.

**Remarks.** Morphological features of the tooth within the genus *Carcharhinus* closely resembles between species. This confusion makes difficult the taxonomic classification of the carcharhinids fossil teeth, especially when they are incomplete and eroded. At least two species have been identified from Chilean marine sediments i.e. *Carcharhinus albimarginatus* (Rüppell, 1837) (Long, 1993; Suárez & Marquardt, 2003) and *Carcharhinus brachyurus* (Günther, 1870) (Suárez *et al.*, 2002; Suárez *et al.*, 2004; Carrillo-Briceño *et al.*, 2013). However, previous studies in modern species have confirmed the presence of other carcharhinids species in Chilean coast. Pequeño & Saez (2003) have reported the presence of *Carcharhinus galapagensis* (Snodgrass & Heller, 1905) from Salas y Gomez

Island and Hernández *et al.* (2008) identified the species *Carcharhinus obscurus* (Lesueur, 1818) from shark fins traded in Chilean market. According to these antecedents, the presence of extinct and modern carcharhinids should be better studied in Chile because there are uncertainty in some of the species used to occur and/or still found in Chilean coast. In the Neogene and Quaternary of Chile, species of genus *Carcharhinus* has been reported from the Miocene and Pliocene in the Bahía Inglesa Formation (Long, 1993; Walsh, 2001; Suárez & Marquardt, 2003; Suárez *et al.*, 2002), Bahía Salado (Suárez & Brito, 2000), Cuenca del tiburón (Emslie & Correa, 2003; Suárez & Marquardt, 2003), La Portada (Suárez & Marquardt, 2003) and Horcón (Carrillo-Briceño *et al.*, 2013).

Order PRISTIOPHORIFORMES Berg, 1958  
Family PRISTIOPHORIDAE Bleeker, 1859

*Pristiophorus* Müller & Henle, 1837

*Pristiophorus* sp.  
(Figure 4F)

**Material.** Thirteen rostral teeth (MALS P-69, MALS P-70, MALS P-71, MALS P-72, MALS P-73, MALS P-74, MALS P-75, MALS P-76, MALS P-77, La Cantera Baja; MALS P-118, Quebrada Las Rosas; MALS P-138, MALS P-139, MALS P-140, La Herradura).

**Description.** The rostral teeth are elongated and slender, with a dorso-ventrally compressed crown. The cutting edges are smooth and without serration. The root is robust with a flat base and is wider than the crown. The root also has a conical shape with the widest part being the base. Most of the specimens are complete and measure between 31 and 32 mm in length.

**Remarks.** *Pristiophorus* is known from the upper Cretaceous to present (Cappetta, 2012). The Neogene fossil record of *Pristiophorus* showed a wide paleobiogeographic distribution in America (Carrillo-Briceño *et al.*, 2015). Nowadays, there is only one species in America *Pristiophorus schroederi* Müller and Henle, 1837, which is distributed in the Bahamas region, Western Central Atlantic (Compagno *et al.*, 2005). The taxonomy of the fossil species of *Pristiophorus* found in the Americas, and especially the rostral teeth have been poorly studied. For this reason we prefer to keep the *Pristiophorus* specimen from the Coquimbo Formation in open nomenclature. The fossil record of *Pristiophorus* in Chile includes Bahía Inglesa (Walsh, 2001; Suárez *et al.*, 2002), Navidad (Suárez & Encinas, 2002; Suárez *et al.*, 2006), Horcón (Carrillo-Briceño *et al.*, 2013) and La Cueva formations (Suárez & Marquardt, 2003).

Order HEXANCHIFORMES Buen, 1926  
Family HEXANCHIDAE Gray, 1851

*Hexanchus* Rafinesque, 1810

*Hexanchus* cf. *griseus*  
(Figures 4G-H)



**Material.** Five upper teeth (MALS P-107, MALS P-108, La Cantera Baja; MALS P-125, Quebrada Las Rosas; MALS P-61, MALS P-226, Quebrada el Culebrón) and a lower lateral tooth (MALS P-109, La Cantera Baja; MALS P-225, Quebrada el Culebrón).

**Description.** Upper teeth are elongated acrocones that are distally inclined, with two or five distally directed cusplets. The root is flattened and subquadrangular. The lower tooth is incomplete with a missing acrocone (MALS P-225). However, five small and distally directed cusplets are present. The complete teeth range between 16 and 21 mm in height and between 8 to 18 mm in width.

**Remarks.** *Hexanchus griseus* is known from the Miocene to the recent (Cione & Reguero, 1994). In Chile, *Hexanchus griseus* and *Hexanchus* sp. have been referred to the Bahía Inglesa and Horcón formations (Long, 1993; Walsh, 2001; Suárez & Marquardt, 2003; Carrillo-Briceño *et al.*, 2013). Suárez & Marquardt (2003) referred isolated teeth of *Hexanchus* associated with cetacean remains from phosphatic layer in Caleta Inglesa and Bahía Chañaral. Arratia & Cione (1996) and Carrillo-Briceño *et al.* (2013) presented a brief summary of the fossil record of *Hexanchus* in South America.

Order MYLIOBATIFORMES Compagno 1973

Family MYLIOBATIDAE Bonaparte 1838

*Myliobatis* Cuvier, 1816

*Myliobatis* sp.

(Figure 4I)

**Material.** Six isolated teeth (MALS P-66, MALS P-230, MALS P-231, MALS P-232, MALS P-233, MALS P-234, La Cantera Baja).

**Description.** The specimens consist of complete isolated teeth of the median files. These teeth are broader than long, with a slightly curved hexagonal contour. In all teeth the crown is practically flat with a smooth occlusal surface. Labial and lingual faces are slightly ornamented. The root displays vascularization type polyaulacorhize. The teeth are between 30 and 50 mm wide.

**Remarks.** The fossil record of *Myliobatis* extends worldwide from the Paleocene to present (Cappetta, 2012). The taxonomic identification of the isolated teeth of *Myliobatis* is extremely difficult because of the high dental variation within this group (Welton & Zinsmeister, 1980; Nishida, 1990). For this reason, a specific taxonomic assignation was not possible and we assigned all specimens from the Coquimbo Formation to *Myliobatis* sp. In the Neogene of Chile, the genus *Myliobatis* has been found in the Bahía Inglesa, La Cueva and Navidad formations (Walsh, 2001; Suárez & Marquardt, 2003; Suárez *et al.*, 2004; Suárez *et al.*, 2002). Summary of the fossil record of *Myliobatis* is discussed in Carrillo-Briceño *et al.* (2013).

## DISCUSSION

Our results revealed at least nine elasmobranch taxa present during the Neogene at the Coquimbo Formation. These include *Carcharocles megalodon*, *Carcharodon carcharias*, *C. plicatilis*, *Isurus* cf. *I. oxyrinchus*, *Pristiophorus* sp., *Odontaspis ferox*, *Carcharhinus* sp., *Hexanchus* cf. *H. griseus* and *Myliobatis* sp. Of these species, *C. megalodon*, *C. plicatilis*, *C. carcharias* and *I. oxyrinchus* have been previously reported from the Coquimbo Formation (e.g. Philippi, 1887; Long, 1993; Suárez & Marquardt, 2003; Le Roux *et al.*, 2006). According to our results, *Odontaspis ferox* and *Pristiophorus* sp. represent the first fossil records for the Coquimbo Formation, although Long (1993) included two further species, *Cetorhinus maximus* and *Aetobatus* sp. for this locality. Our assemblage includes at least two extinct species: *C. megalodon* and *C. plicatilis*. With the exception of *Pristiophorus* sp., the rest of the elasmobranch taxa found in this study are related to the living species distributed along the Pacific coast of South America (e.g. Egaña & McCosker, 1984; Acuña *et al.*, 2002; Hernández & Lamilla, 2004; Hernández *et al.*, 2008).

The Neogene is characterized as a period of intense climatic, tectonic and biotic change (Zachos, 2001; Dekens *et al.*, 2007; Dowsett & Robinson, 2009; Garreaud *et al.*, 2010). For instance, events such as the hyper-aridity of the Atacama Desert and the reactivation of the modern flow of the Humboldt Current produced important changes in the Neogene climate conditions (Garreaud *et al.*, 2010; Tsuchi, 2002). Studies of elasmobranch fossils suggest vast variations in species richness in the South Pacific (Villafañá & Rivadeneira, 2014). The elasmobranch fossil record of the Coquimbo Formation would suggest differences in the dynamics of elasmobranch biodiversity. Species, such as *Carcharocles megalodon*, *Carcharodon plicatilis* and *Pristiophorus* sp. probably became extinct due to climatic and biotic changes that occurred during the late Neogene. Rivadeneira & Marquet (2007) suggested that the diversity in the composition of mollusk species decreased during the Miocene and Pliocene along the South American Pacific coast. A similar tendency in decreasing diversity was shown with the extinction of marine mammals (Valenzuela-Toro *et al.*, 2013), and sea birds (Chávez *et al.*, 2007). The extinction of several macro-vertebrates may reflect the macro-evolutionary dynamics of those taxa in the temperate Pacific coast of South America.

In addition, we found differences in the distribution of extinct elasmobranch species in comparison to modern species. For example, the fossil distribution of *Carcharodon carcharias* and *Hexanchus* increased southward (Villafañá & Rivadeneira 2013). In contrast, the presence of shark species such as *Isurus oxyrinchus*, *Odontaspis ferox*, *Carcharhinus* sp. and *Myliobatis* sp. decreased southward (Villafañá & Rivadeneira 2013). Analyzing the distribution of genus *Carcharias* in the South Pacific Ocean, it might be attributed to the abrupt temperature decrease during the middle Pliocene and Pleistocene (Cione *et al.*, 2007). This change in the temperature eventually also affected the

distribution other species. However, Villafañá & Rivadeneira (2013) suggested that the fluctuation in elasmobranch biodiversity might also be explained by ecological and life history aspects such as body size, modes of reproduction, and migration patterns.

In order to explain the variability in richness and composition of marine fossil records in Chile, it would be valuable to increase the sampling effort of fossil records from the Coquimbo Formation and other Neogene units. Furthermore, more sampling sites should be determined and reviewed. The well-preserved sedimentary sequence of the Coquimbo Formation is an unexplored field. A better description of the elasmobranch fossil records will set the baseline to gain a better understanding of the ecology, distribution and evolution of taxa that ranged the oceans millions of years ago.

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